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13. ABSTRACT (Maximum 200 words)

Report developed under SBIR contract for Topic BMDO02-011. This report discusses the Phase I results in achieving light emission from Erbium doped Gallium Nitride materials. Erbium is a rare earth material which can emit at specific wavelengths of light, both in the visible and infrared regions of the spectrum. Erbium-doped layers were grown in GaN-based junctions by the molecular beam processing technique. The effects of Erbium in GaN were characterized using photoluminescence (PL) and catholuminescence (CL). Prototype devices were fabricated and electrically pumped light emission from the Er LEDs was observed.

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Hetero-Junction pumped Er-Light Emitter for Integrated Optical Communication

Contract #F49620-02-C-0069

Contract Monitor: Dr. Gernot Pomrenke
AFSOR/NE

Final Report

Submitted by
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1. Background Discussion

Optical interconnect is envisioned to be the future solution to data flow bottle neck for on-chip, or between chips and between modules. High speed, high bandwidth, noise and interference immunity, and electrical isolation are the perceived advantages of optical over electrical data transmission. To realize such concepts a versatile light emitter must be demonstrated. Our proposed concept utilizes the fact that rare-earth elements possess many atomic transitions, and their properties could lead to the realization of desired high bandwidth communication. When coupled with Si-based detector sand electronic drivers, they form a signal transceiver module easily integrated to the standard silicon processing. This transceiver can be used for both free space and waveguided communication. The realization could thus lead to opto-electronic integrated circuit (OEIC) and photonic chips.

Rare earth (RE) element-based electroluminescence (EL) has generated much attention for a number of optoelectronic applications. Much research has been carried out on Er-doped silicon for such purpose but due to its narrow bandgap Si has not proved to be a good host for Er. Recent demonstration of high intensity emission of erbium-doped GaN grown on Si suggests it to be a good choice for light emitter, and should have much less thermal quenching problems due to the much higher bandgap of the GaN host. The extensive body of work on GaN doped with rare earths has revealed the occurrence of significant lumimescence at 0.8 eV (1540 nm in wavelength), 1.2 eV (1000 nm), 2.3-2.3 eV (537-558 nm) and other energy levels. The various transitions are displayed in Figure 1(a), and Figure 1(b) represented the cathodoluminescence (CL) and photoluminescence (PL, inset) measurement of the GaN(Er) thin film deposited at SVTA, showing the presence of these transitions.
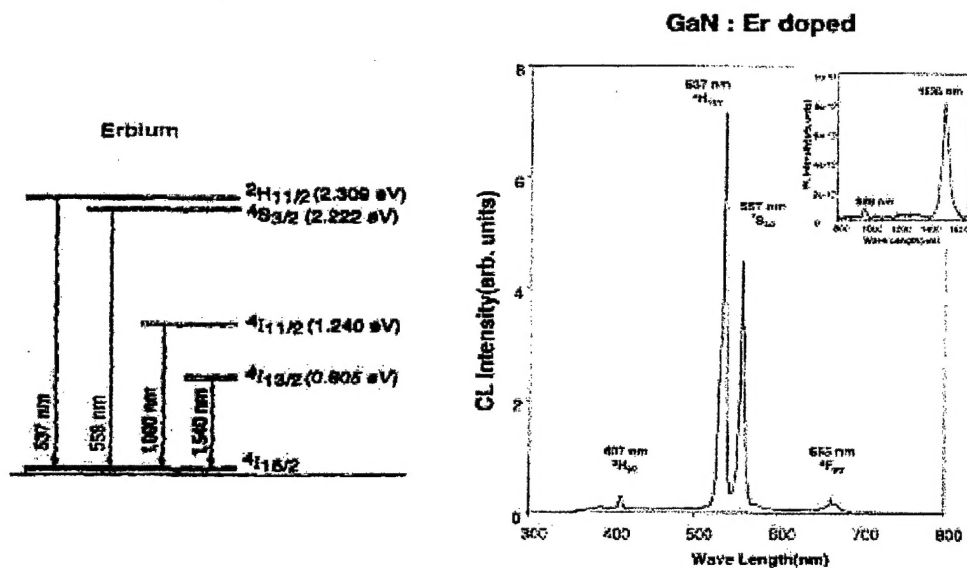
Figure 1. Energy diagram illustration of the 4f levels of Er in GaN (a), and the cathodoluminescence measurement of the important spectral lines in material produced at SVTA (b).

During this Phase I project we have carried out many deposition runs of Er-doped thin films on silicon wafers, characterized their electrical and optical properties, and fabricated Schottky light emitting diode (LED) that demonstrated light emitting. The films are shown to exhibit very good optical properties as evidenced by their strong luminescence. It is worth commenting that one could exploit the multiple wavelength emission for simultaneous communication in several channels to increase the data transmission, a concept we would like to investigate further in the follow-on program. Since it can be pumped at different wavelengths, optically addressable logic gates can be realized.

The major accomplishments on this project are summarized below:

- **Strong luminescence observed at both visible and infrared wavelengths**

- **Co-doping of oxygen and silicon performed to enhance layer conductivity**

- **Schottky and pin LED's fabricated and demonstrated**

- **Heterojunction of Er-doped GaN on silicon shown for detector applications**

- **Luminescence efficiency enhanced by quantum well structure in LED**

- **Optical interconnect concepts proposed for further investigation**

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2. Phase I Work Results

2.1. Er-doped Nitride Thin Film Growth

The (Al)GaN:Er films have been grown in a Molecular Beam Epitaxy (MBE) system on Si(111) and sapphire wafers. The Er flux is generated by a compact electron beam evaporation source capable of reaching 3500°C. An advantage of this source is that it produces a much higher flux than that achievable by conventional effusion cell, leading to high Er incorporation in the epi-layers. A radio frequency (RF)-plasma source is used to generate active nitrogen species. The emission levels of the plasma are monitored through an optical port located at the rear of the source. Solid Al and Ga sources are used to complete the growth AlGaN layers of various compositions. The substrate heater of the system used for this program was modified to allow for the high growth temperatures (>1000°C) that are necessary for the clean desorption of the silicon wafer surface. Figure 1 displays a typical Er-containing nitride structure for investigation.

The basic growth procedure is as follows. The Si substrates are initally etched in HF acid to remove any native oxide. They are then mounted into non-bonded substrate blocks and loaded quickly (within 5 minutes) into the molecular beam epitaxy system. The blocks are heated to 300°C in the analysis chamber of the MBE system to remove any residual adsorbed gases. They are transferred into the growth chamber and the substrate temperature slowly ramped to 850°C as determined by an optical pyrometer. At this temperature, the Si surface shows excellent reflection high energy electron diffraction (RHEED) patterns indicating that the surface is free of any native oxide. For (111)-oriented silicon wafers this RHEED pattern is the so-called 7x7 superstructure.

Next a thin buffer layer of AlN (200 Å) is deposited at 800°C . The atomic nitrogen source is lit at a flow rate and power which corresponds to an effective growth rate of 0.5 um/hr. The shutters for both Al and N are subsequently opened to initiate growth of a buffer layer. (No signs of SiN formation is observed in the RHEED pattern during the 30 seconds required to light the plasma in the RF source.)
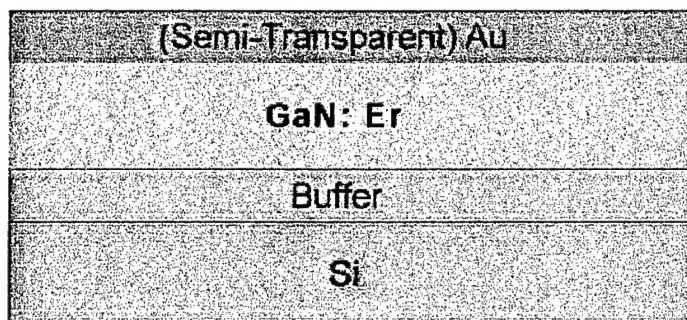

Figure 1. Schematic of a typical structure of Er incorporated layer for investigation.

The (Al)GaN layers are then deposited onto the AlN buffer at 760°C. The RHEED pattern quickly becomes "streaky" for a good quality growth surface. The layer is typically grown at 760°C at a growth rate of 0.5 μm/hr. Even at relatively high Er incorporation the RHEED pattern can still exhibit good quality for the right growth conditions. During this project various dopant materials such as oxygen, silicon and magnesium were also introduced into the layer so that their effect on the material properties can be investigated.

2.2. Material Characterization

Prior to processing, various material characterization tests take place to determine the properties for visible and 1.54 micron emission of the samples. In particular photoluminescence (PL) and cathodoluminescence were used extensively. The PL measurement setup is displayed in Figure 2, where light from an Argon laser (typically 40 – 50 micro-W) is directed to the sample, and a monochromator is used to scan for any emitted light. In this way a PL spectrum is obtained such as the one presented
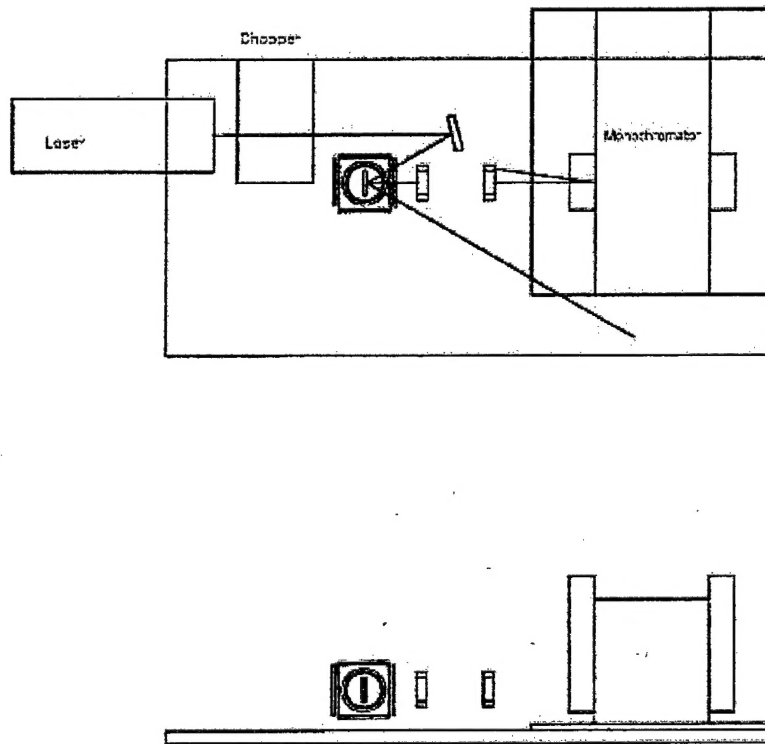

Figure 2. Photoluminescence (PL) measurement setup.

in Figure3 for one of the initial GaN:Er samples. More PL results will be discussed later together with other experimental parameters. Several other excitation sources are also available, including a 980 nm diode laser for excitation of different atomic level. Once the initial characterization tests are completed the sample can be processed for further evaluation.
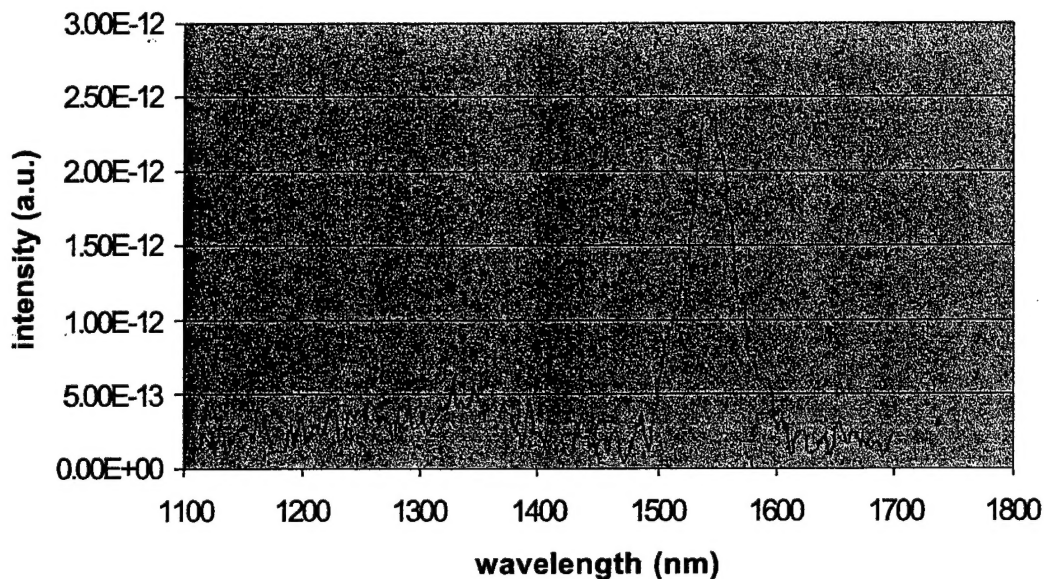

Figure 3. PL spectrum of a GaN:Er/AlGaN/Si sample grown for this program.

Catholuminescence (CL) is a particularly useful tool for this program, because it provides an in-situ way of measuring the properties of the thin film. It is an optical emission technique which uses a high energy electron beam to excite the thin film materials. Dispersion of the fluorescence induced by the electrons allows the band gap of the deposited material to be determined. The optical quality of the deposited film can be evaluated from the FWHM of the band-edge emission, and qualitative assessment of the doping level can be made from the structure of the CL emission. The wide-bandgap nitrides in general exhibit very bright luminescence, and Er-doped materials display very sharp atomic transition lines. This can be done under vacuum without removing the sample from the growth chamber. Figure 4 displays the CL of a representative sample. The characteristic Er visible lines (537 and 558 nm) are extremely sharp and much more intense than the band edge peak (a broad peak centered around 360 nm). The CL intensity appears to scale with Er incorporation. Note also that the brightness of the atomic transition is not necessarily depending on the quality of the host AlGaN materials grown over a wide range of experimental parameters, and we have observed as bright luminescence in amorphous SiO2 and Si3N4 host layers.
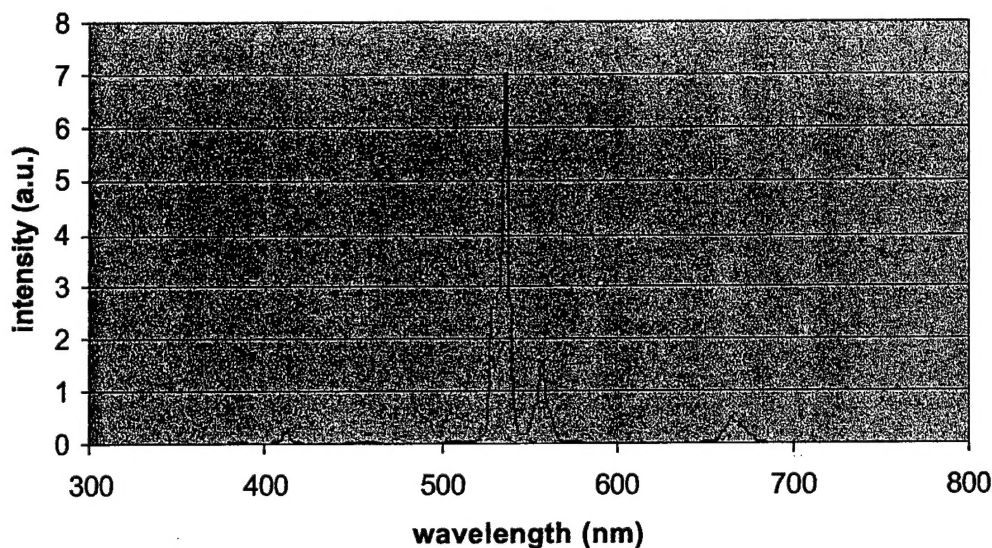
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Figure 4. The CL spectrum of GaN:Er grown on Si showing the characteristically sharp Er lines at 537 and 558 nm.

These results indicated that using PL and CL the basic optical emission characteristics of the Er-doped samples covering the visible and infrared regions can be easily determined.

2.3. Sample Processing and test

Test samples with the cross section schematically shown in Figure 1 are processed. The sample is first cleaned with an acetone ultrasonic bath which is followed by a methanol bath and ends with a DI water rinse. Metals are then deposited. The front-side contacts are patterned with Microposit S1818 photoresist and completed by a lift-off. The n-metal contacts consist of Ti/Mo/Ti/Au layers while the p-metal contact is formed by Ni/Ti/Au (when doing p/n diode structure.) The planar structure of the finished diode is shown in Figure 5. The junction area of the device is 0.59 mm^2. A metal ring contact defines the optically active area of the diode, which is a circular with an inner diameter of 798 micron, corresponding to an area of 0.50 mm^2

The processed samples are evaluated on a probe station. Both electrical and optical tests can be readily made in a setup shown in Figure 6. Electrical measurements were made with a HP 4156A parametric analyzer or a bias voltage can be supplied with a power supply (not shown) to check for light emission. The probe station is also aligned with optical testing equipment that can measure the optical response of a test sample. Typical I-V curves from one of the processed samples in the dark and under illumination are shown in Figure 7. The ambient light effect is small but very discernable when the scale is expanded (in b).
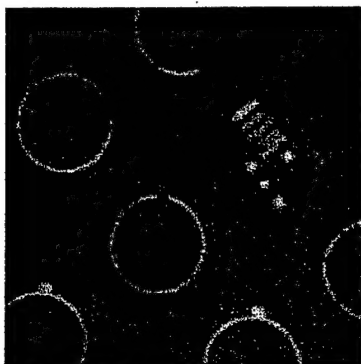
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Figure 5. Photograph of processed GaN:Er diodes, with the probe touching one of the contacting pad.
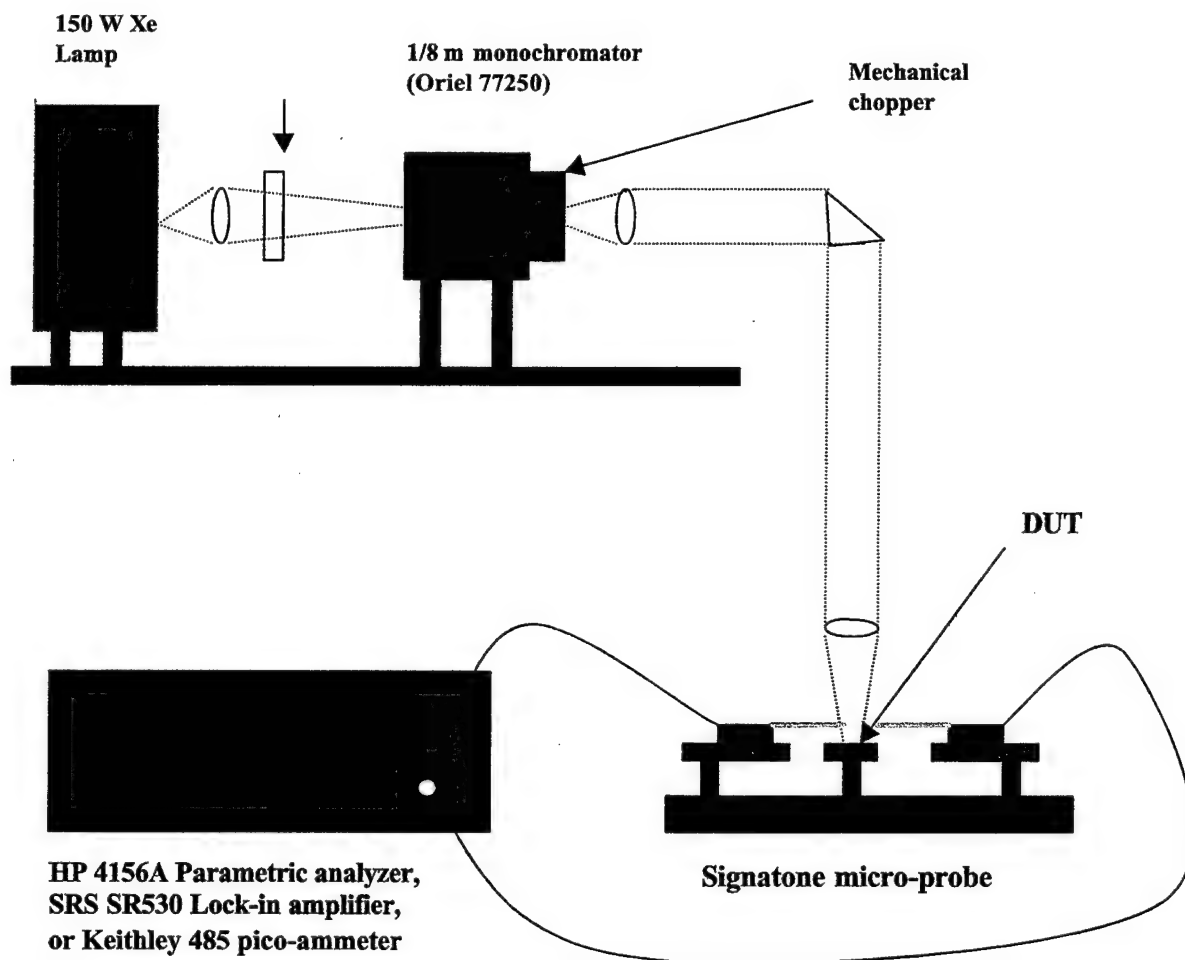
Figure 6. The sample is placed on a probe station and can then be tested electrically with a parametric analyzer or optically as shown.
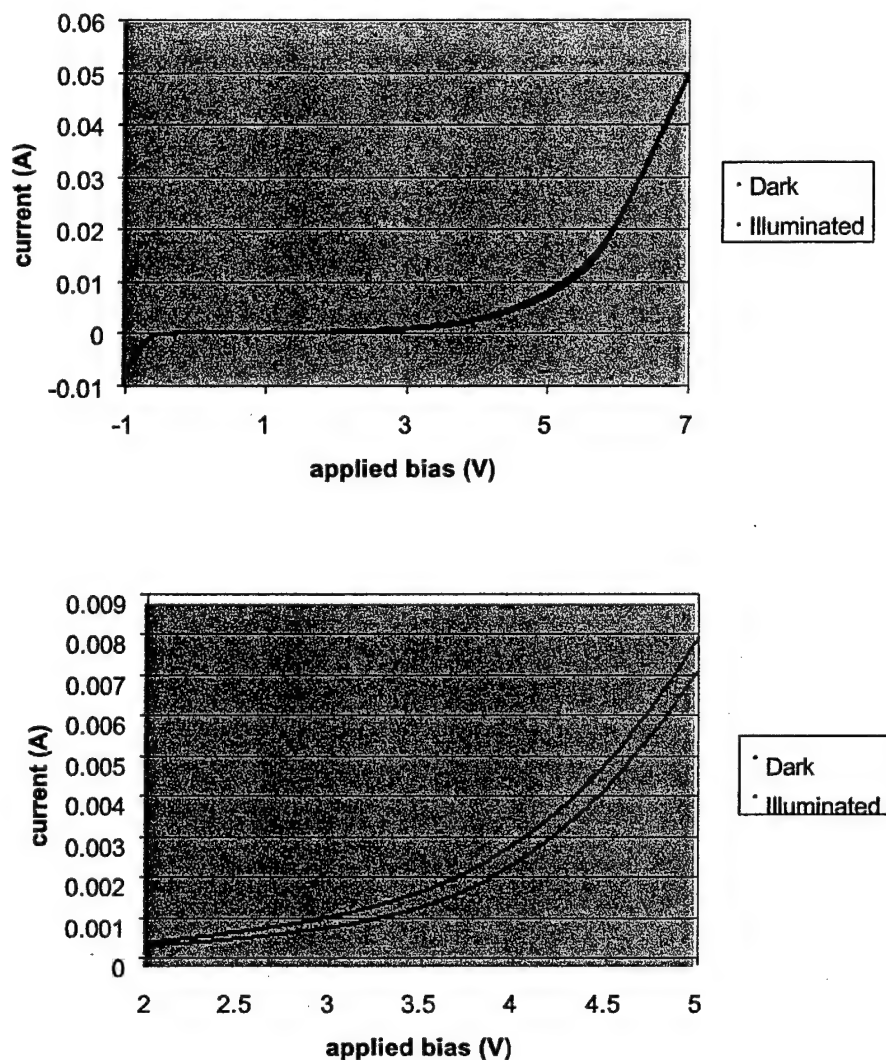
Figure 7. (a) I-V curves measured from one of the processed GaN:Er samples showing effect of response under illumination. (b) The same I-V curves showing more clearly the diode action of the GaN:Er diode to light.

This observation is somewhat unexpected, given the Er absorption is atomic and the photo-generated carriers would be difficult to extract out of the atoms. A possibility is the host nitride layer is acting as a Schottky detector. That presents the possibility of integrated transceiver of a pair of light emitter and detector.

To investigate further, a p-GaN (Mg)/GaN:Er/n-Si sample was fabricated. The device was measured in the photo-voltaic mode, i.e. unbiased. As displayed in Figure 8, its response is quite strong and covers a wide spectral range. Note there is a peak around

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365 nm, characteristic of GaN bandgap, and a broad signal band ranging into the infrared wavelengths.
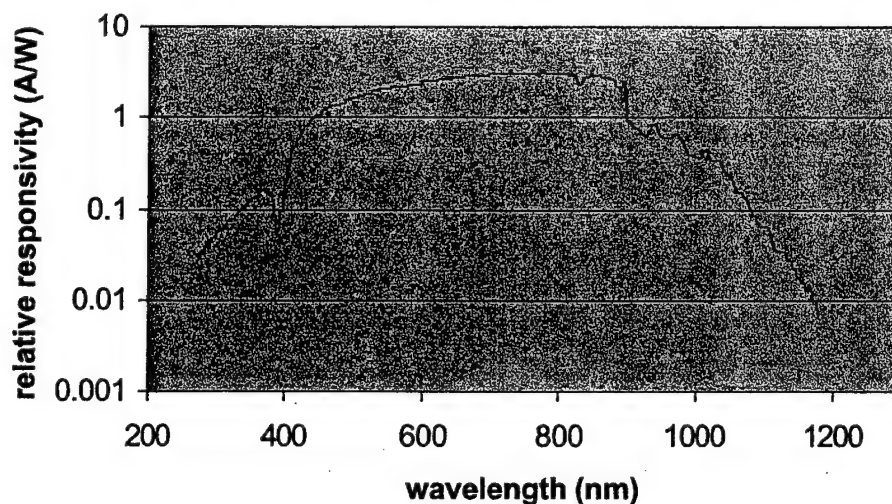

Figure 8. Spectral response of a p-GaN/GaN:Er/n-Si (pin) sample on silicon.

We believe the response came from a combination of GaN and the underlying silicon. The sharper peak around 365 nm coincides with the bandgap of GaN. Since the bottom contact is made to the backside of the silicon wafer, photo-carriers generated in both the GaN thin film and the silicon substrate will drift across the field created by the junction. The broad response curve appears to be that of silicon (the bandgap of which corresponds to about 1100 nm). Note also that absorption of GaN at above bandgap wavelength reduces the signal of silicon at shorter than visible wavelengths (400 nm).
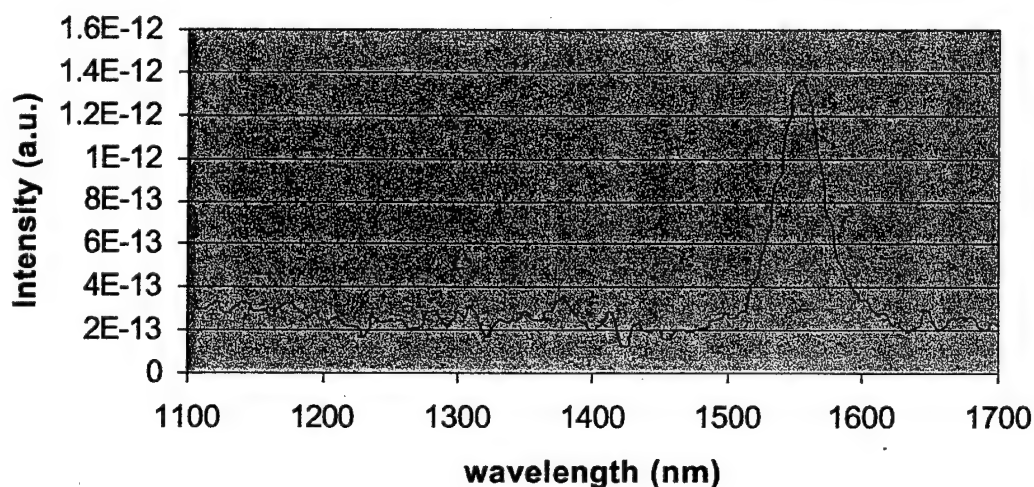

Figure 9. IR PL of the p-GaN/GaN:Er/n-Si (pin) sample from the Ar ion laser.

By doping the GaN:Er layer p-type using Mg, the characteristic lumniescence at around 1540 nm was not impeded. The PL of the sample in Figure 9 displays the same Er-peak as a first demonstration of Er emission from a p/n junction.

Erbium doped GaN samples are very resistive, which is manifested by high biasing voltage to induce emission. Such high bias is not practical for electronic applications and causes frequent breakdown and inefficient use of the energy. We therefore investigated the effect of co-doping by oxygen and silicon. Low flux of oxygen is introduced by metering a fixed amount with the nitrogen flow, and silicon is evaporated from an electron-beam heated source. Figure 10 illustrates a series of experiments that shows the resistance of a 200 nm thick Er-doped GaN as function of oxygen co-doping. Note that the resistance of the thin film can be substantially lowered by such technique.

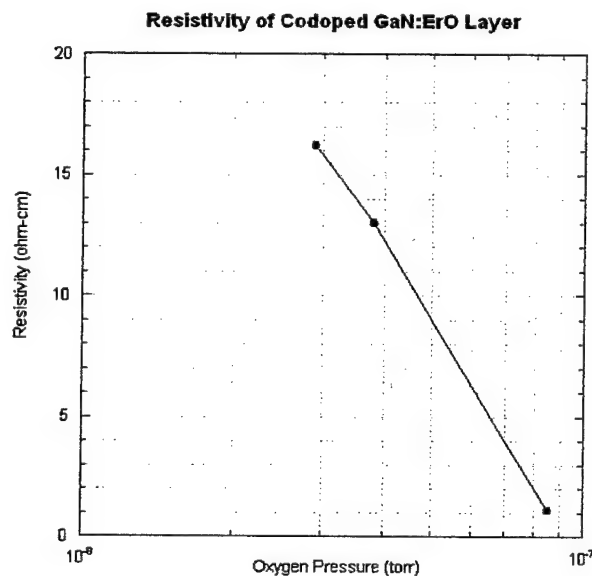**Resistivity of Codoped GaN:ErO Layer**

Figure 10. Resistivity of the Er doped layer as function of oxygen flux.

A set of pin LED structures on sapphire was studied for light emission enhancement. Optimized devices can then be further investigated for the follow-on work. A GaN:Er thin film (ranging from 7 to 200 nm) was first grown on n-type bottom AlGaN/GaN contact and cladding layer which was supplied by Prof. H.X. Jiang of Kansas State University (in collaboration with Dr. Zavada of ARO.) Before the top p-layer was deposited, CL of the sample was measured. Figure 11 displays the characteristic twin visible spectral peaks in the CL spectrum (this time the Er-doped layer is over the MOVPE grown material.) Note that in most of these CL measurements the Er- spectral peaks are observed to be much more prominent compared to those of the nitride host, whether it is MBE and MOVPE grown.
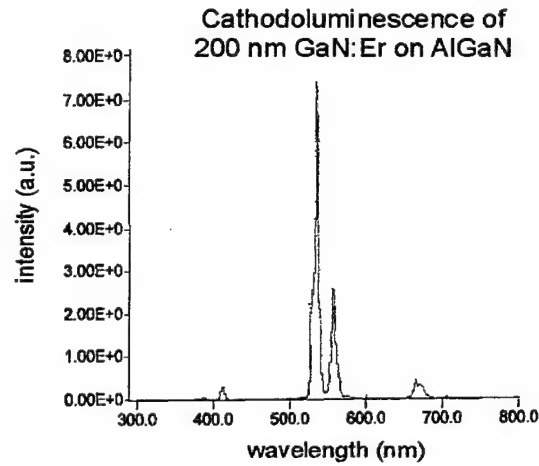
Cathodoluminescence of
200 nm GaN:Er on AlGaN

Figure 11. Er-doped layer on n- AlGaN/GaN with sapphire as substrate. The sample was measured before the top p-layer was deposited.

Above gap Excitation

Argon laser (UV): ?$_{ex}$: 336-363 nm
Pump Power : ~ 40 mW (power meter)
High Voltage : 200 V
Slit width : 5 mm
Filter : RG 850, UG 1
Scan range : 800-1800nm
@ 80nm/min

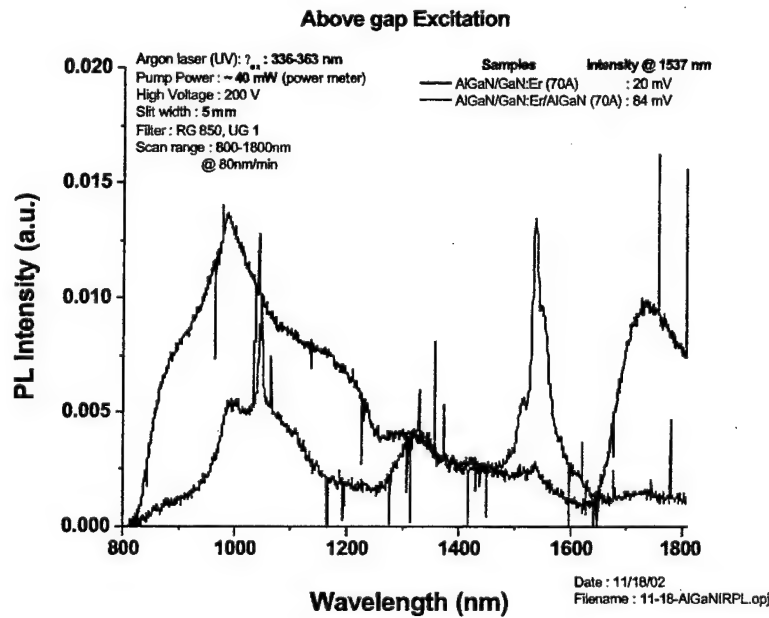| Samples	Intensity @ 1537 nm
AlGaN/GaN:Er (70A)	: 20 mV
AlGaN/GaN:Er/AlGaN (70A)	: 84 mV

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Figure 12 presents a comparison of the PL of the layer before and after the top p-layer AlGaN was deposited. Under the UV 336 nm line of the Ar laser, note the QW structure showed enhancement (the red trace).

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To investigate the quantum well effect, part of the sample was used to put a AlGaN cap layer on. As displayed in the PL spectra in Figure 12, with the above bandgap excitation (wavelength$_{ex}$~ 336 nm), the infrared PL from the QW structures (curve in red) showed a marked improvement compared to that of the uncapped films (in black). The PL intensity increased and the spectra showed less defect-related emission. The enhanced PL properties may be due to more effective confinement of electron-hole pairs in the QW region. These structures exhibited a variety of interesting optical properties that have important implications for optical amplification and light emitting devices. Such improved structures will be further developed in Phase II program.

To demonstrated electrically activated light emission a Schottky diode structure is fabricated, formed by depositing a semi-transparent gold metal on top of the GaN:Er layer (grown on Si wafer.) The photo in Figure 13 displays a 'standard' mask showing various levels of metal layers. Electrical contacts are then made to the top metal and the bottom conductive silicon. When the diode was biased emission can be observed through the top layer.
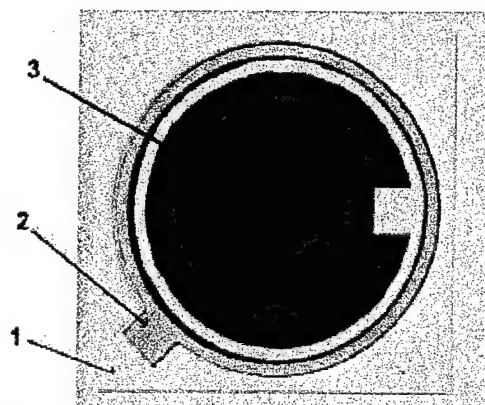
Optical micrograph of a Si-based emitter.
1. Ohmic metallization.
2. Schottky metal contact ring.
3. Semi-transparent Schottky metallization.

Figure 13. Microscope photo of a diode structure used in the program.

3. New Concept Investigation

Here we explore several significant concepts to take advantage of the unique properties of Er-doped materials. We propose them for further investigation in Phase II.

3.1 Dual Color transceiver and quantum computing

As we have shown, rare earth Er doped gallium nitride (GaN) thin film Schottky diode emits in both the visible (green, 537 and 558 nm) and infrared (1000 and 1540 nm) wavelengths. Such device may be integrated with waveguides and detectors to form functional optoelectronic chip. One can envision a novel transceiver unit consisting of a pair of light sources made of GaN:Er emitter and two sensors of Si and Si-Ge, the latter used for visible and infrared detection. Detectors for the wavelengths of interest are well established technology. For example silicon pin diode can be quite readily formed by either dopant implantation or diffusion. For infrared detection SiGe alloy or Ge itself can be the choice due to their compatibility with silicon processing. The bandgap of Ge is about 0.7 eV so it is sensitive to about 1700 nm radiation. There has been significant amount of work to develop Ge detector for optical communication applications (e.g. G.Masini, L. Colace, G. Assanto, H.C. Luan, K. Wada and L.C. Kimerling, SPIE Proc. 3953, p.103 (2000)). One of the emitters and the SiGe detector diodes can be covered by an over-layer of silicon which transmits only radiation of the energy below its bandgap and acts as a optical pass filter for signal longer than 1100 nm in wavelength. This simple unit thus contains a pair each of visible and infrared transmitter and receiver.

This device is designed to transmit both visible and infrared signals. If one treats the visible signal as "1" and the infrared "0". Signals can then be coded into a series of "1"s and "0"s, as represented in Figure 14. In its simplest form the signal consists of equal time period of the "1"s and "0"s as in early part of the signal train. Additional information can be carried by varying the time pulse of the signals as indicated in the second portion of the signal train, and by having both light emitters on. The latter can also form the basis for logic gates (AND gate, for instance). In summary the concept takes advantage of the light emission characteristic of the Er emission for optical transmission, interconnect, computing applications, leading to opto-electronic integrated circuit (OEIC).

Figure 15 explores various schematics of communications, including chip-to-chip (or module-to-module) via fiber, waveguide or free space. The concept of dual color communication is further illustrated in c and d of the figure. With the advances of material science, nanotechnology and optics, quantum computing is an emerging field. In the ubiquitous world of digital computing, data is broken down into bits, with each bit being 0 or 1. Quantum computing uses qubits, pieces of data which can be either 0, 1 or something in between. With more than two states possible for a qubit, scientists predict that quantum computing can execute calculations millions or billions times faster than current supercomputers. The multispectral emission from the erbium states can be employed as optical interconnects in future quantum computers. For example, a 3-state

qubit can be transmitted using the visible line (state 1), the infrared line (state 2) or no emission (state 3).
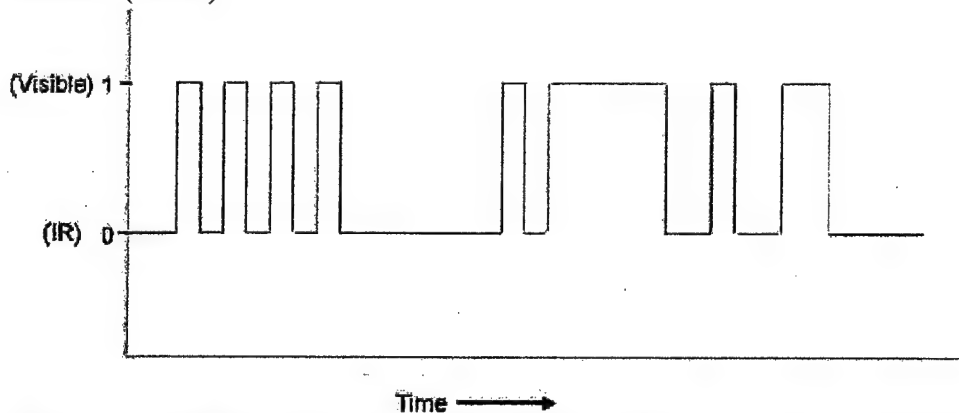

Figure 14. Digitized signal train using both the visible and infrared channels. "1"s are represented by the visible emission and the "0"s by the infrared. The first part of the signal train consists of equal time interval of the signals. Additional information can be carried by varying the time pulse of these signals as in second part of the signal train.
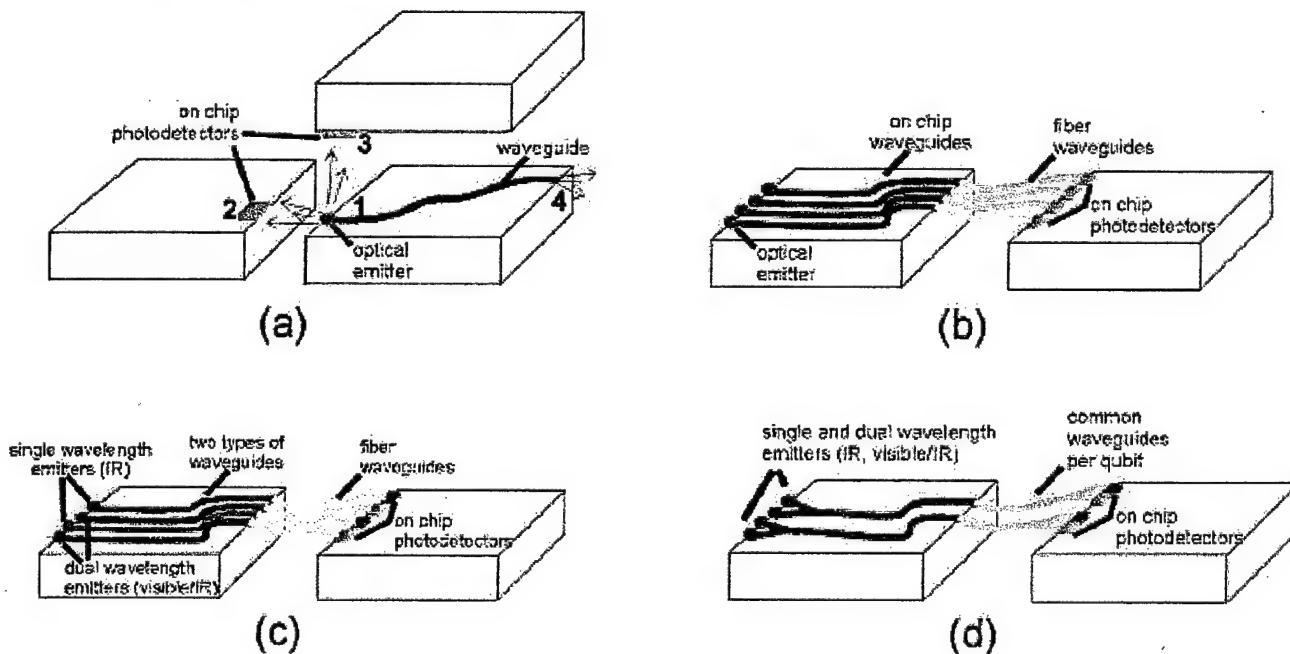

Figure 15. Various illustrations of communication means. Chip-to-chip (or module-to-module) communication may be achieved via fiber, waveguide or free space (a & b). Example of dual color transmission (c). Example of quantum computing (d).

To make the technology even more silicon-compatible, we have also evaluate Er-doped SiN thin films fabricated by reactive deposition of Si and nitrogen plasma. The PL result displayed in Figure 16 indicated SiN can be a very promising candidate for the same applications. The PL intensity from the Er-doping is quite strong and SiN deposition and etching are certainly routine steps in the silicon fabrication process.
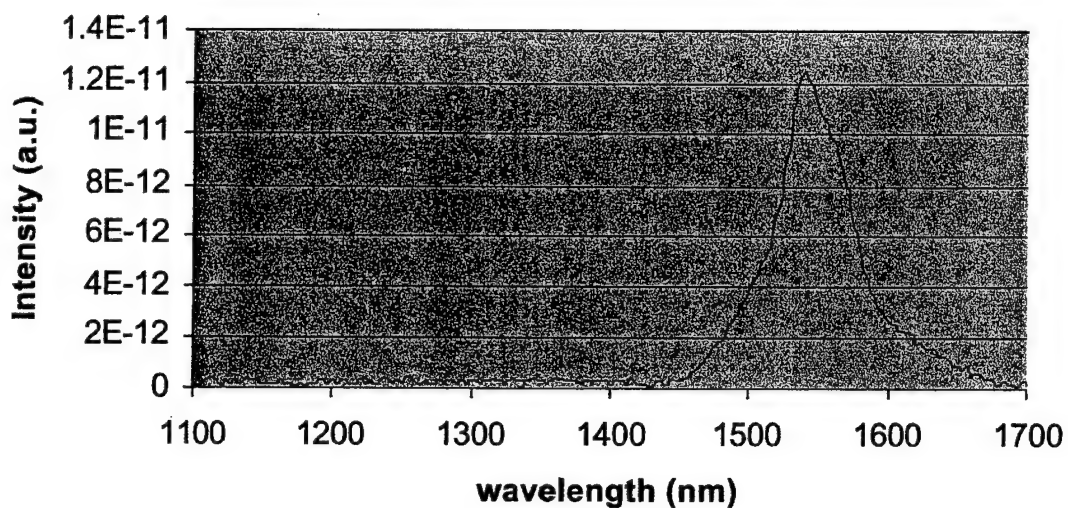

Figure 16. Photo-luminescence of Er doped SiN layer grown on silicon showing the characteristic 1540 nm PL.

3.2 High Frequency Device Concept

Applications of the optical interconnect involves high speed data transmission. One of the often used example, for example, is the optical clock. In order to assess the feasibility of high frequency applications, we analyzed the limit of high-speed modulation for Si/GaN:Er diodes fabricated in the Phase I program.

The following equation can be used to estimate the maximum modulation frequency limited by the RC-constant :

$$f_{max} = 1/(2*Pi*RC),$$

where R is the load resistance and C is the device capacitance. The capacitance of the Si/GaN:Er diodes with 100×100 micron^2 is measured to be ~5pF. If the Si/GaN:Er diode is used with a 50 Ohm load resistance, the f_{max} is calculated to be 5.88×10^8 Hz, i.e., 588 MHz. Reducing the C value by a factor of 10, e.g. down to 0.5 pF would result in modulation frequency limitation of 5.88 GHz.

This estimate gives the limitation due to RC consideration, but not due to internal limiting factors such as optical relaxation times. The optical relaxation times for emission through Er impurity could be a predominant factor limiting the device performance, so must be taken into account in device application.

3.2a. Hetero-Avalanche Diode Concept

We have fabricated vertical Er:GaN/Si and Er:AlN/Si hetero-avalanche structure. The device operates in avalanche mode using the well known fact that Si exhibits the largest avalanche factor, and is able to generate a high flux of excited carriers once the process is started. When biased, non-equilibrium carriers from silicon inject through the junction interface into n-type GaN:Er (AlN:Er) and recombine through the Er-related levels located deep in the bandgap. The optical emission efficiency in such diodes is determined by Er-impurity concentration and capture cross-section for Er impurities, the latter is a function of the position of the Er-level in the GaN(AlN) bandgap. Another important factor influencing the electroluminescence intensity is the injection efficiency from Si into GaN(AlN). Due to the large difference in the bandgap between GaN and Si a high forward bias is required to provide efficient injection into the GaN. In the forward bias configuration, this structure showed light emission at green wavelength around wavelength = 520 nm as well as emission around wavelength=1550nm. The emission is due to recombination through optically active Er-impurities located in GaN(AlN) near the Si/GaN(AlN) interface. This device thus have the potential of producing high frequency light pulses and its modulation will be investigated in the follow-on program.

3.2b. Erbium Doped HEMT AlGaN/GaN Emitter

Using the Er-doped lateral AlGaN/GaN structure described below for optical interconnects can significantly reduce the RC component by means of reduction of the device capacitance. Due to very low parasitic capacitance in HEMTs, the direct modulation frequencies of this structure can be extended to tens of gigahertz. In the structure shown below (Fig. 17) we propose to utilize Er-impurity pumped non-equilibrium electrons and holes, generated near the gate-drain region of AlGaN/GaN HEMTs during impact ionization process near the critical electric field. Fig. 17 schematically illustrates the proposed structure and identifies the region of impact ionization where excitation of the Er-impurities occurs.
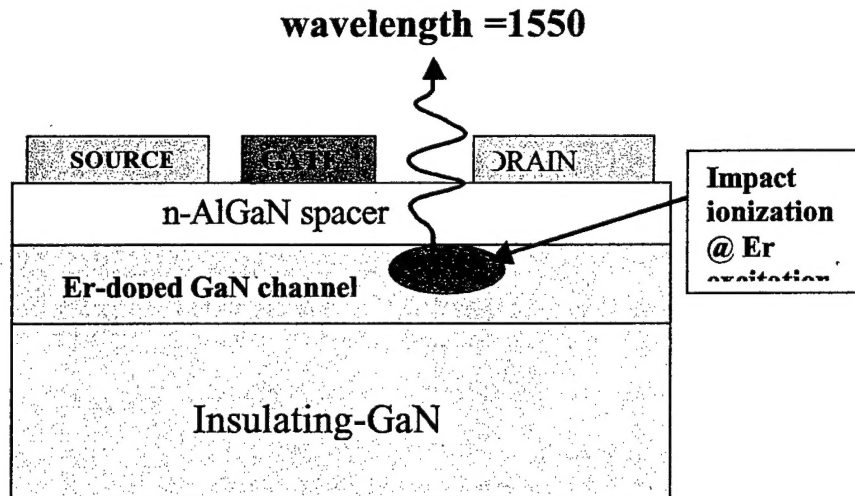

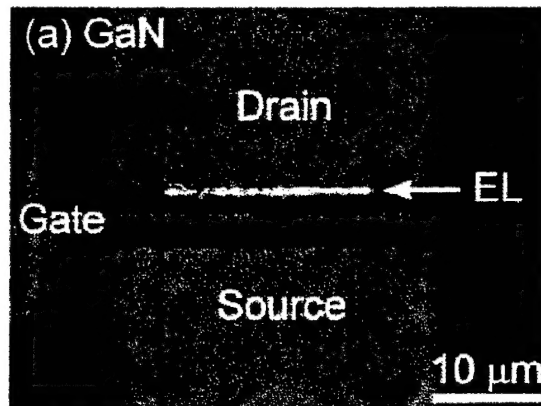**Fig. 17 Schematic of a novel AlGaN/GaN HEMT with Erbium-doped channel.**

Fig. 18. EL distributions in (a) GaN HEMT at V_{DS}= 70V and V_{GS} = -2V . (Takeshi NAKAO, Yutaka OHNO, Mitsutoshi AKITA, Shigeru KISHIMOTO, Koichi MAEZAWA, Takashi MIZUTANI, "Electroluminescence in AlGaN/GaN High Electron Mobility Transistors under High Bias Voltage", Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 1990–1991)

Electroluminescence (EL) in GaN high electron mobility transistors (HEMTs) biased at high drain-source (D-S) voltages was investigated previously (Takeshi NAKAO, Yutaka OHNO, Mitsutoshi AKITA, Shigeru KISHIMOTO, Koichi MAEZAWA, Takashi MIZUTANI, "Electroluminescence in AlGaN/GaN High Electron Mobility Transistors under High Bias Voltage", Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 1990–1991). This paper reports that electroluminescence was observed at the drain edge where the high-field region is formed as shown in Fig. 18.

This is somewhat different from the case of GaAs HEMTs where luminescence has been observed at the gate edge (For example, see H. Niwa, Y. Ohno, S. Kishimoto, T. Mizutani, H. Yamazaki and T. Taniguchi: Jpn. J. Appl. Phys. 37 (1998) 1343). Optical emission spectrum from the gate-drain (G-D) was also measured in the reference T. Nakao et al cited above. Luminescence with spectral range of visible to near-infrared light corresponding to energies less than the band gap energy was observed with polarization in the direction parallel to the drain current.[See Fig. 19].This luminescence spectrum overlaps with Erbium absorption line at 980 nm and can be used for efficient optical pumping of Erbium impurities in GaN or other host materials.
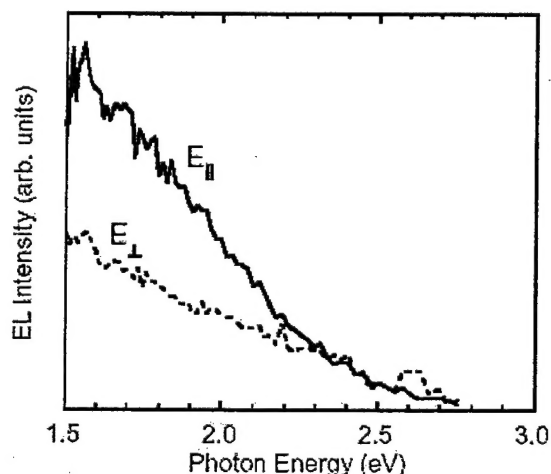

Fig. 19. EL spectra of the GaN HEMT measured through a polarization filter [Ref. T. Nakao et al cited above] $E_{parallel}$ and $E_{perpendicular}$ components are parallel and perpendicular to the drain current, respectively.

We expect that electrical modulation frequency of the AlGaN/GaN HEMT devices with Er-doped channel will be limited by the device geometry, such as source-drain separation and gate length and width. It is well established that ft and $fmax$ of AlGaN/GaN HEMTs with sub-micron gates exceeds 100 GHz, so the proposed device should not be different from those. However maximum modulation frequencie of optical emission from such Er-doped HEMT device may be limited by the relaxation time of Er-impurities in GaN.

In order to transfer optical information from one point to another on a Si chip, planar optical waveguides can be used. Both types of structures described above can be monolithically coupled to low loss thin film optical waveguides. The insertion loss could

be minimized to less than 0.5 dB-cm per coupling. Assuming 0.2-0.3 db-cm of internal waveguide loss this would give 1.2 - 1–3 db-cm per optical interconnect. This total optical interconnect loss seems to be reasonable for practical applications.

The planar waveguides can be made of SiGeON materials with high optical reflective index deposited by PECVD or MBE. The composition of this material should be chosen to closely match the thermal expansion coefficient of Silicon. This will prevent bowing, and cracking, which contributes to additional optical loss.

4. Summary Conclusion

We have successfully performed the Phase I project by demonstrating workable LED emission from Er doped GaN grown directly on silicon. Several on chip and chip-to-chip communication concepts have been proposed, including the new concept of dual wave band (visible and infrared) communication which could lead to new optical devices. By demonstrating Er doped SiN material the integrated optoelectronic chip concept may be more easily implemented. To address the high frequency requirements for applications such as on-chip optical clock, we have analyzed the device time constant and proposed novel device structures to achieve ultra-high frequency data transmission. We plan to explore these concepts further in the follow-on program.